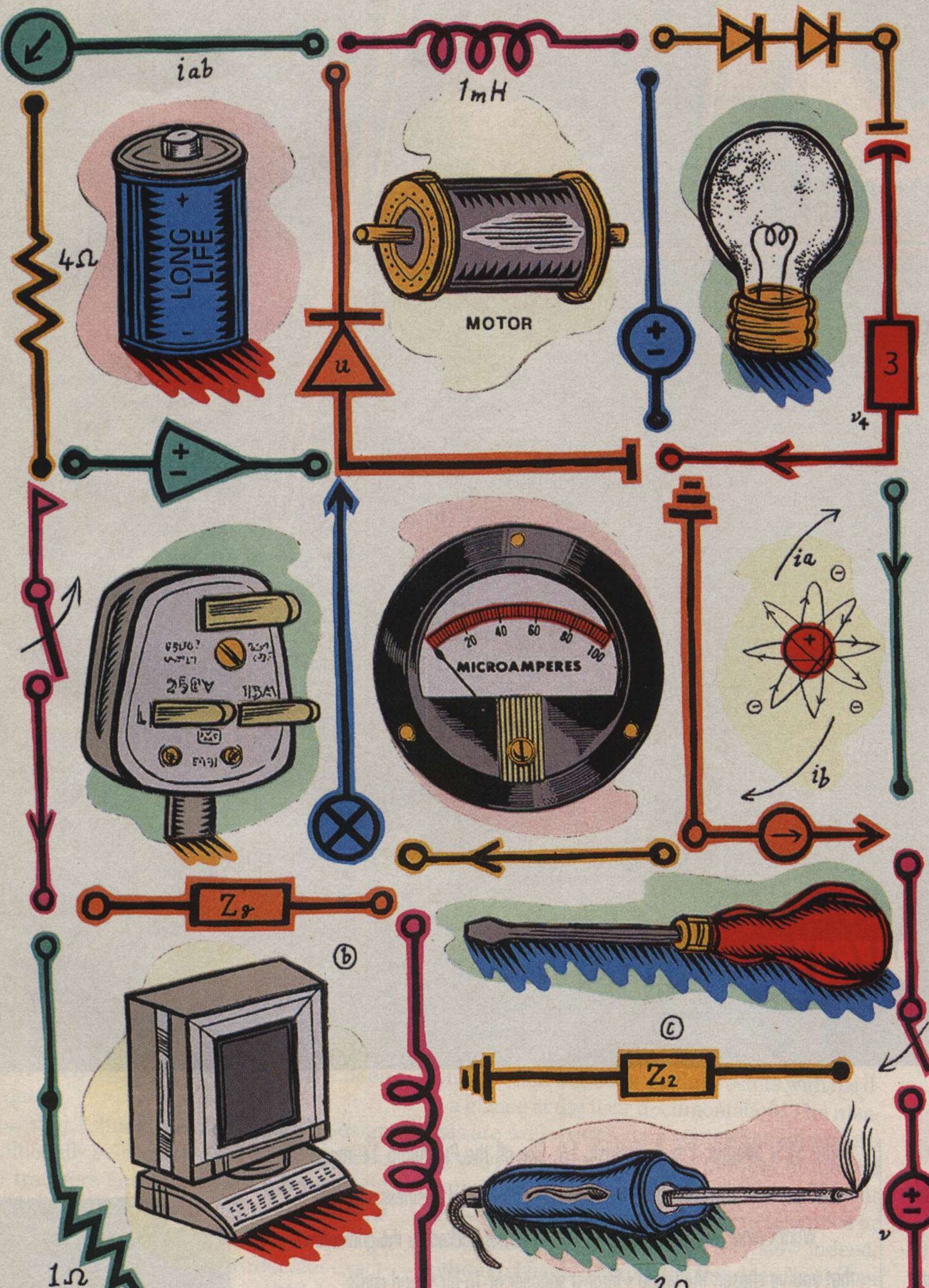
Only make believe

These days you can't design a computer chip without a computer. In the second part of our introduction to modelling, **Mike Bedford** gets round to circuit simulation



Last month we launched this series on computer modelling and simulation with a glimpse into the world of economics. That subject was chosen for its topical appeal, but in other respects it could be considered a rather odd choice. In the public eye, economic modellers vie only with the politicians who quote their forecasts as objects of scorn and derision. We went some way towards exonerating the experts by explaining why the economy is so difficult to simulate, but in so doing begged the question why computer models should be constructed at all if they can't make credible predictions.

Before delving any further into the technology of modelling and simulation, therefore, we really need to present the other side of the picture and prove that simulation is indeed an honourable undertaking. This month, then, we'll consider the application of computer simulation to another field – electronic engineering design – where, with a bit of luck, it'll show itself able to model the real world reliably and accurately.

The task

THE WORLD OF ELECTRONIC ENGINEERING will be alien to the majority of readers. Many will have a general interest in the field, but most will have no detailed knowledge. So we'll start with a bit of background on the mysteries of the soldering iron and the oscilloscope to help put this application into context. The circuit simulation which follows will provide an illustration of the technology which can be interpreted at whatever level of technical detail you're comfortable with – ignoring the occasional bit of jargon shouldn't prevent you seeing what's going on. For readers who do have a practical interest, we'll go on to provide details of some real products available for this kind of task.

The first step in the electronic design process is the one we can think of as the 'real' design: the working out of just what components are required to do the job in hand, and how they're going to interconnect. This process requires a mix of theoretical knowledge, experi-

Joseph Silcott

ence, and the application of information from component manufacturers' data sheets. The end result will be a circuit diagram, and the task is traditionally accomplished with pencil and paper. PC Cad packages are now frequently employed for the purpose, but this type of software only assists in the actual drafting process – it doesn't lessen the need for expert knowledge of electronic engineering.

In a perfect world, the end of this step would be the end of the electronic design engineer's involvement; the circuit diagram would be passed on to a printed circuit board (PCB) designer, and the unit would subsequently go into production. In practice, if this were to happen a lot of frustrated customers would follow in the designer's wake. Unfortunately, except for trivially simple designs, circuits don't work first time!

This being the case, the design engineer doesn't back out after the initial theoretical work, but instead enters a second phase of the design: prototyping and testing. This can be a time-consuming and expensive exercise. With simple circuits, the prototype can be built on a piece of Veroboard – an insulating board, drilled on a 0.1" grid, with copper strips on the back joining together all holes on the same horizontal line. By placing component leads through the holes, soldering them onto the copper strips, making breaks as necessary in these strips, and adding wires on the front to patch extra connections, the circuit is built up – albeit in a rather inelegant fashion.

Fit to print

In all but the simplest of cases, this approach would prove very long-winded and – because of the likelihood of creating 'rats' nests' – make fault-finding very difficult. For anything approaching the complexity of the main board in a PC, therefore, prototyping involves designing and building up a proper PCB, very much like the finished product.

PCBs, like Veroboards, are made of an insulating material with copper tracks etched onto them. The difference is that PCBs are designed for a specific circuit, as opposed to being general-purpose. The tracks, therefore, aren't necessarily straight parallel lines – they take whatever path is necessary to create the required connections. Because tracks are normally required to cross each other, PCBs usually have tracks on both sides, and frequently on a number of layers in the middle too. All in all, designing a PCB is quite a task. The PCB will have to be designed sooner or later in any case, but remember that at the start you're dealing with an unproved circuit, so the process may need to be carried out all over again once any teething problems have been ironed out.

In passing, I should mention that PCB design has traditionally been carried out by laying down opaque transfers and tapes onto a translucent sheet, but is now usually done using Cad systems. One stage on from Cad is fully automated PCB design, in which the software decides exactly where to place each track. If the initial drafting of the circuit diagram was done using a Cad system, the interconnection information, which an 'auto-routeing' system will require, may already be available in a suitable machine-readable format.

Once the board has been designed, it's manufactured using a photochemical process and then passed back to the design engineer, or a technician, to 'build it up' – that is, solder on the components. Of course, if the circuit were in production the populating of the board with the components would be automated using 'pick and place' machines and flow-soldering techniques. At the prototyping stage, however, it just isn't worth programming manufacturing equipment for a small run so, once again, we're talking about a time-consuming process: building the circuit by hand using a soldering iron, pliers, and wire cutters.

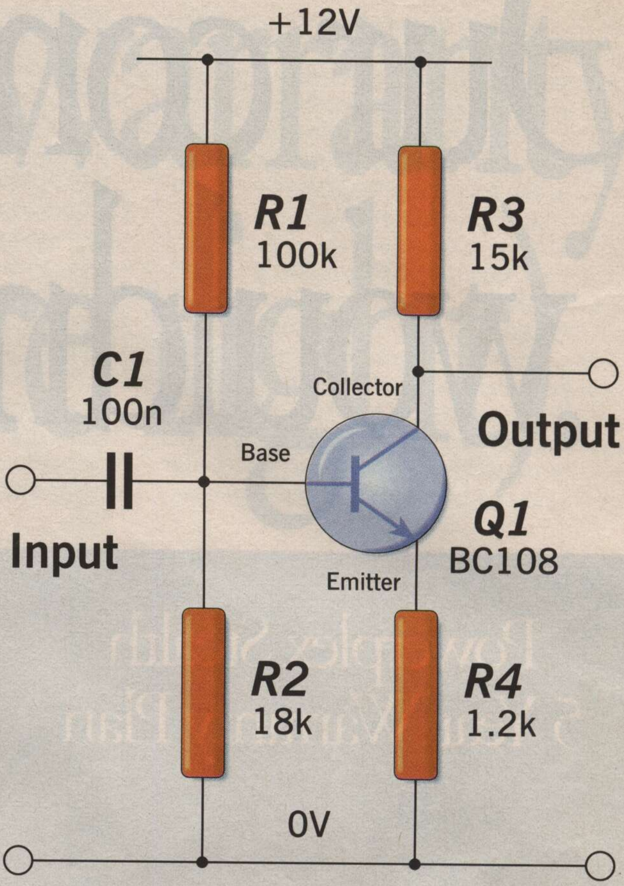
Eventually our design engineer will have in his hand the realisation of what he or she designed on paper some weeks – or months – before. It would be nice to think that the engineer's task is now simply to prove the thing works, but in practice it more frequently involves finding out why it *doesn't* work and establishing what changes need to be made in order to get it to perform as expected.

A further complication is that any faults could just as easily be due to a mistake in the prototyping process – ie the PCB design or the building up of the board – as one in the design process. All in all, the testing phase could last many weeks and will involve the board, a signal generator, a test meter, an oscilloscope, a soldering iron, a pair of wire cutters, and a lot of frustration.

Let's pretend

Having read the foregoing text, you probably won't be surprised that this month's topic, circuit simulation, is a way of saving a great deal of time in the prototyping and testing phase. What follows is a practical comparison of the conventional and simulated approaches, using a very simple circuit, to illustrate the principles involved without getting heavily into the electronics.

The software packages I used were *SPICE Age*, a circuit simulation package, and *GESECA*, the complementary schematic capture program (see the Contacts section at the end of this article for more details of these and other products). I found the user interfaces of both programs very intuitive, and was soon getting results with hardly a glance at the user documentation. The manuals are well written (in a somewhat light-hearted way) and include quite a number of tutorial examples. My only niggle is that in transient analysis over a sweep of component tolerance or temperatures *SPICE Age* was very slow indeed, although I have to admit that this does involve an awful lot of arithmetic. I would really have to recommend a minimum of a 486DX-33 for use with this product combination – a sentiment which was shared by the supplier.



① **The example circuit**

Figure 1 shows the diagram of the circuit I used to contrast the two approaches to design verification. It's a trivially simple design, but this should enable those without any electronics background to follow the design process, while adequately illustrating the features of the *SPICE Age* package.

There's one obvious disadvantage to picking such a simple circuit: the time saving achieved by the use of simulation will be much less than with a circuit of more typical complexity. In order to address this point, we'll look at some facts and figures later concerning the hypothetical development of a larger circuit.

Those who do have more than a passing interest in electronics will recognise the circuit shown in Figure 1 as a single-stage common-emitter transistor amplifier. Although there are some deliberate errors in this circuit, it's intended to operate in the audio frequency range (that is, about 50Hz to 20kHz), have a gain of about 5, and accept an input signal with an amplitude of up to 1V – that is, a peak-to-peak of 2V.

The traditional approach

FIGURE 2 (SEE PANEL) ILLUSTRATE THE STEPS involved in prototyping, testing, and correcting the amplifier circuit. The captions indicate just what each step involves.

Let's take a more detailed look at the testing and remedial phase. The first job was to check up on the DC operating conditions. This involved applying power but no input signal to the circuit,

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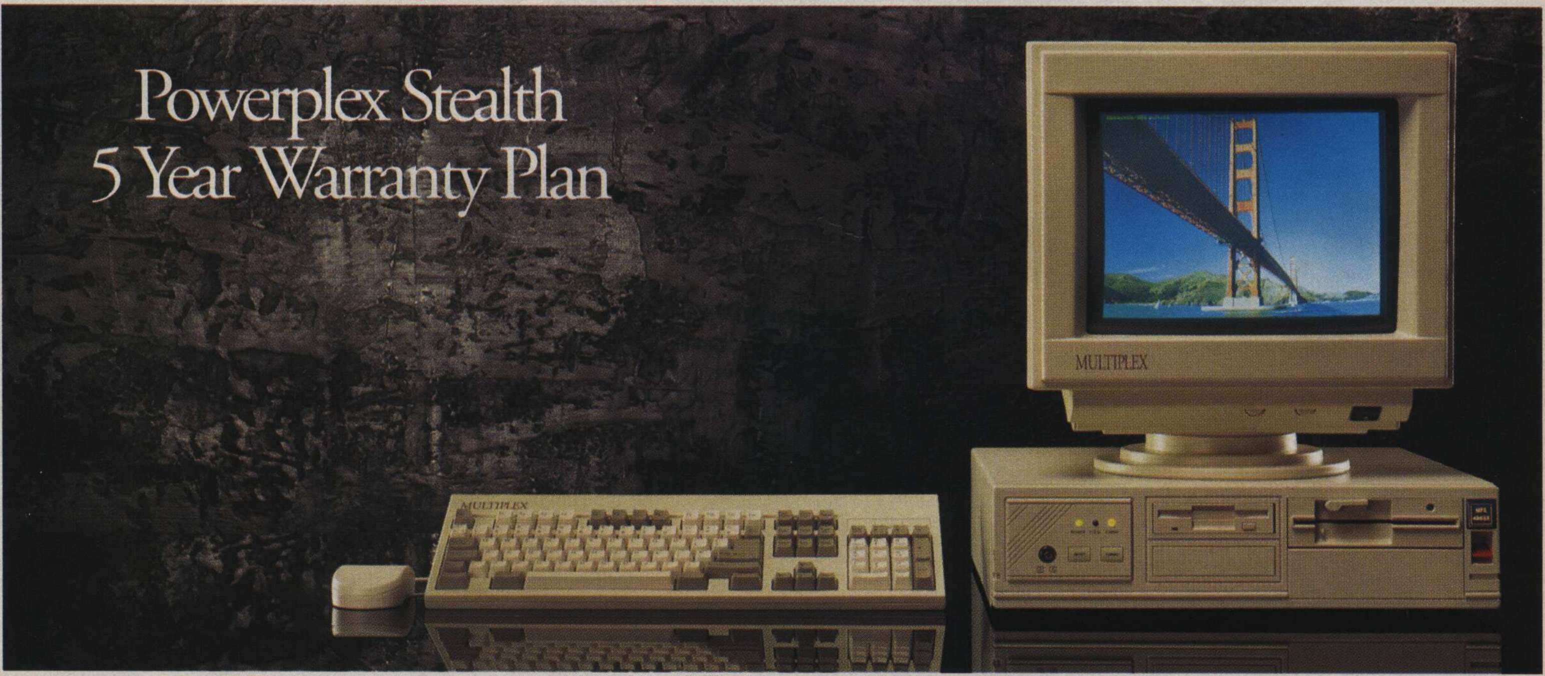

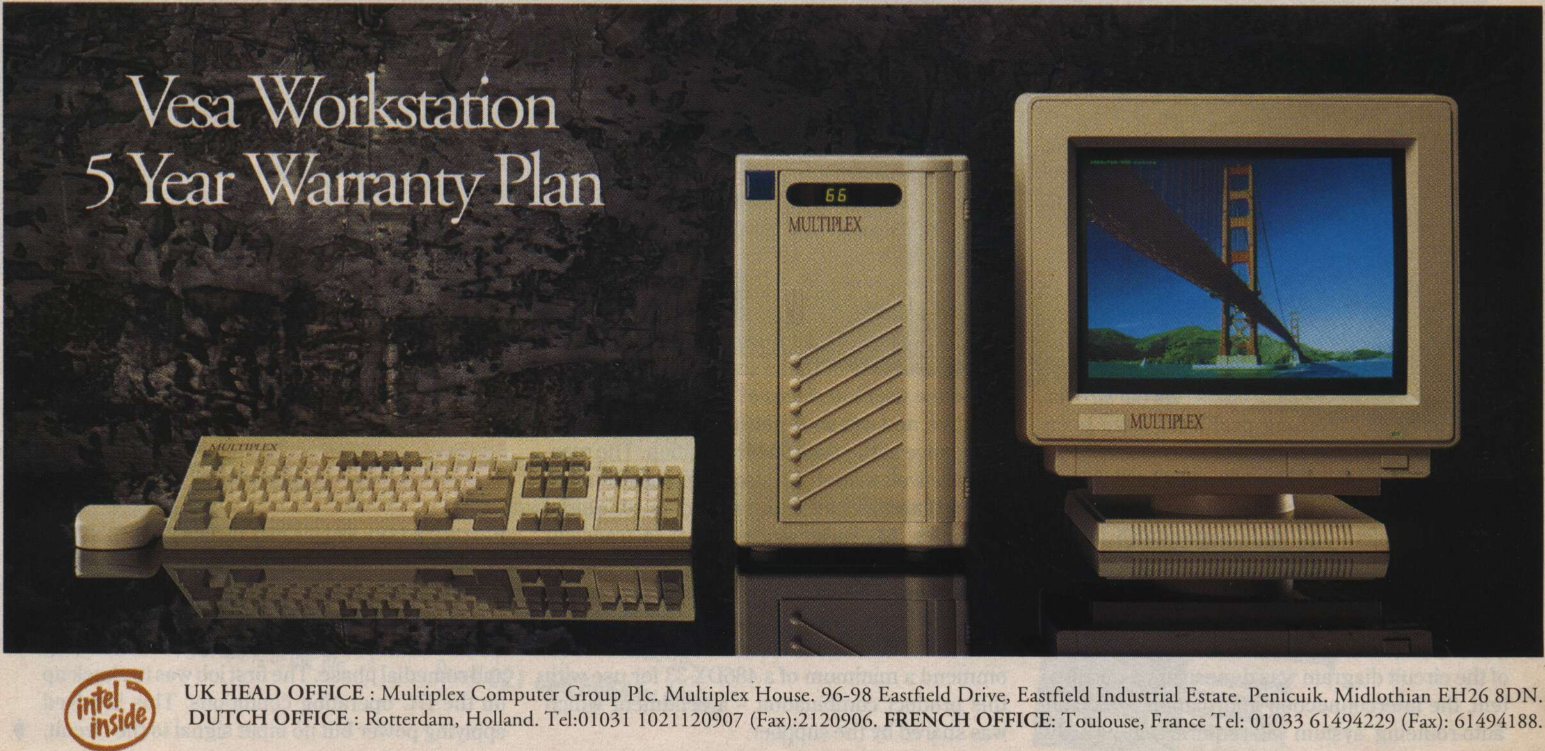

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and checking with a test meter that the voltage at certain key places is as expected. In particular, the potential divider, which consists of R1 and R2, should cause the base of the transistor to be at a potential of about 1.6V, and this in turn should bias it for linear operation. Using a voltmeter, this voltage was measured and was found to be as expected. So far, so good.

If I'd chosen to investigate a bit further, I would have found something amiss with the collector voltage, which should have been just over half the supply voltage. However, since finding a problem at this stage would have obviated the need to carry out some of the other tests, I bypassed this in order to illustrate the testing procedure fully.

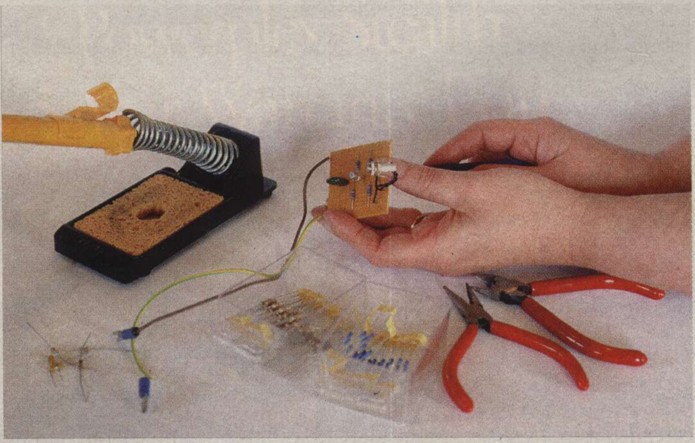
Had the circuit been more complicated, the next step would have been to apply a suitable input signal and then trace it through the circuit using an oscilloscope. In this simple case, however, I decided first of all to judge the performance by ear – this is, of course, the ultimate test of an audio amplifier! – and then, if necessary, use an oscilloscope to diagnose any problems.

In real life this amplifier stage would probably be used to feed a more powerful amplifier which could drive a loudspeaker. But although it won't drive a speaker by itself, our amplifier does have enough capacity to drive a high-impedance crystal earpiece. So I connected an audio signal generator to the input, and the earpiece between the collector of the transistor and 0V, and tried some experiments using a sine wave input. Starting mid-range for both amplitude and frequency, the output sounded OK. On increasing the amplitude of the input much beyond 0.5V, however, distortion became evident, suggesting that the amplifier was probably 'clipping' the signal even with an input amplitude well below the design specification of 1V. The other noticeable anomaly was that the output appeared to decrease significantly at low frequencies. All in all, it seemed the circuit wasn't functioning as expected. Time to take a look at some waveforms with the oscilloscope.

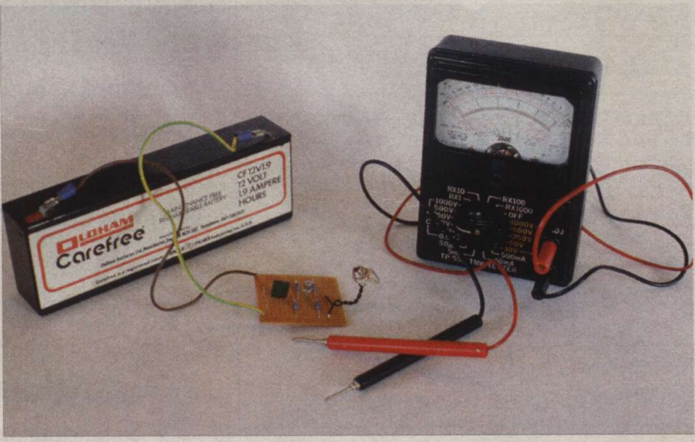
Learning to scope

The only signal we're really interested in at this stage is that at the output, so I attached the oscilloscope probe to the same point as the earpiece, namely the collector of the transistor. Returning the signal generator to just less than 0.5V and a frequency of about 1kHz, the trace on the oscilloscope looked to be far from a pure sine wave –

❷ The traditional approach

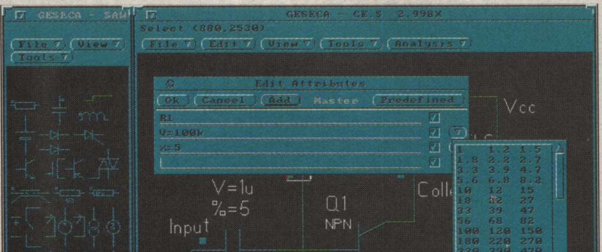


1 The prototype is built up manually on Veroboard by pushing component leads through the perforations and soldering them to the pre-formed conducting strips, cutting strips or adding wires where necessary



2 The power supply is applied and the DC operating conditions checked up on. So far, nothing seems amiss

❸ The simulation approach

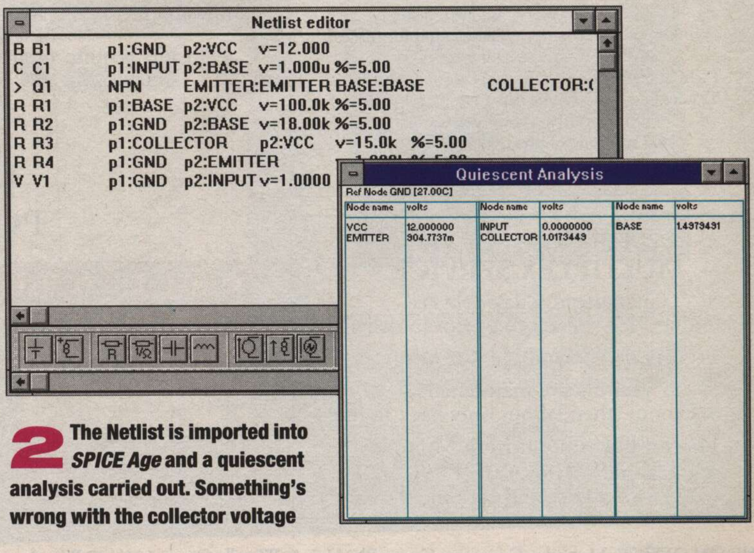


R1

V=100k

%=5

1 The circuit is defined on the PC using *GESECA*, a circuit design package



```
B B1     p1:GND    p2:VCC    v=12.000
C C1     p1:INPUT  p2:BASE   v=1.000u %=5.00
> Q1     NPN       EMITTER:EMITTER BASE:BASE       COLLECTOR:(
R R1     p1:BASE   p2:VCC    v=100.0k %=5.00
R R2     p1:GND    p2:BASE   v=18.00k %=5.00
R R3     p1:COLLECTOR        p2:VCC    v=15.0k  %=5.00
R R4     p1:GND    p2:EMITTER
V V1     p1:GND    p2:INPUT  v=1.0000
```

```
Ref Node GND [27.00C]
Node name  volts       Node name  volts       Node name  volts
VCC        12.000000   INPUT      0.0000000   BASE       1.4979491
EMITTER    904.7737m   COLLECTOR  1.0173449
```

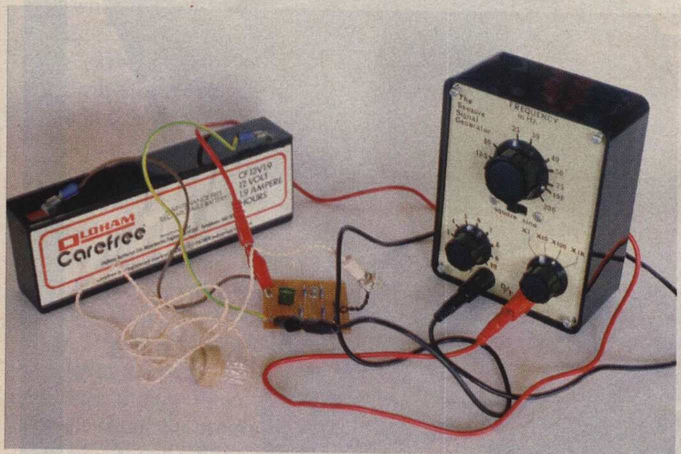
2 The Netlist is imported into *SPICE Age* and a quiescent analysis carried out. Something's wrong with the collector voltage even at an input level which sounded OK by ear. This seemed odd, so a bit of further investigation with the test meter was undertaken. It soon became obvious that since the previous stage of the test the supply voltage had dropped well below 12V – the battery needing charging! This in turn had changed the transistor biasing, something which had already been checked, and so significantly modified the amplifier characteristics. All of this serves to underline the point that anomalies during testing may point to an error in the prototyping or the testing itself rather than in the design.

I replaced the battery, and a clean sine wave was now observed. However, the amplitude was already at the maximum 12V, suggesting that the gain of the amplifier was much greater than the 5 which was intended. Sure enough, on increasing the amplitude of the input much beyond 1V peak-to-peak, the output waveform proved to be clipped – quite clearly the source of the audible distortion noted earlier.

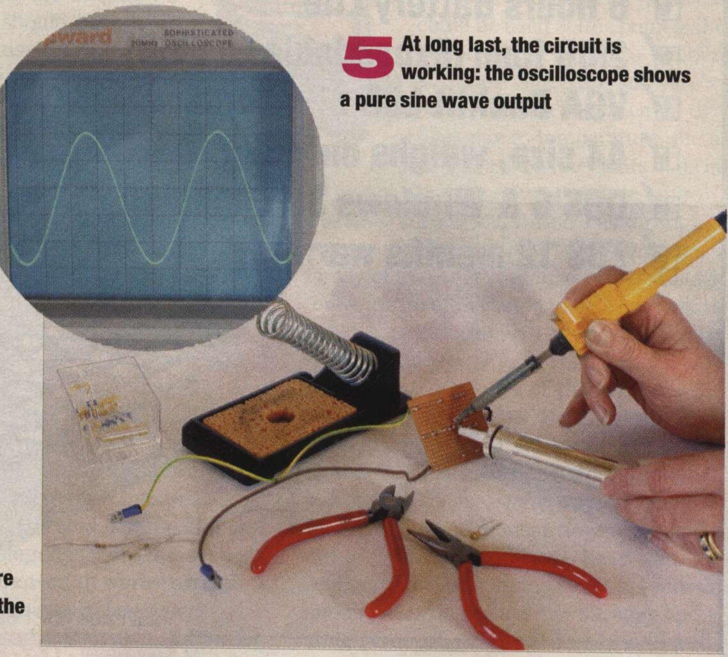
A quick calculation revealed what was amiss. The gain of a common-emitter amplifier is defined by the ratio of the collector resistor to the emitter resistor, which in this case equates to 15k/1.2k, or about 12. This was obviously the first mistake in the design. The collector resistor was changed to 5.6k and a repeat of the test showed that the gain had reduced to about 5 and that a 1V amplitude input could therefore be applied without causing distortion at the output.

Now to the other problem: an apparent loss of output at low frequencies. After making the above modification, the expected output was achieved for middle frequencies, as read off the oscilloscope. As the frequency was reduced much below 100Hz, however, the amplitude of the output was reduced, even with a constant 1V input signal. At about 80Hz, the output was down to about half its amplitude at 1kHz, and at 50Hz there really wasn't much output at all. Evidently something was restricting the bandwidth at the low-frequency end of the spectrum.

The low-frequency cut-off is defined by the product of the base capacitor with the parallel combination of the two base resistors and the input resistance of the transistor stage. Doing the sums for this circuit shows that this cut-off is too low, so we've now identified the second of the obvious problems. If either resistor had been changed, the other resistor connected to the base would also have needed changing in order to keep the transistor's biasing correct. ➧

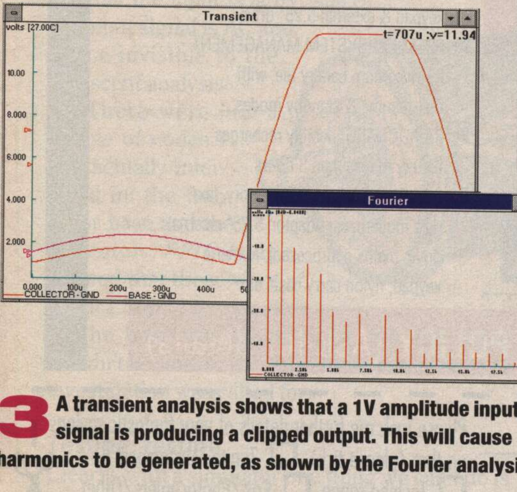


3 With a signal generator attached, the output is monitored on a crystal earpiece. When this doesn't sound too good, the signal is checked with an oscilloscope, proving that there is indeed distortion

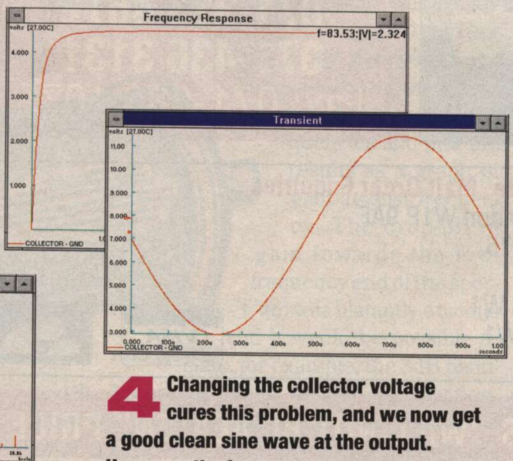


4 Some components are changed to try to fix the problems

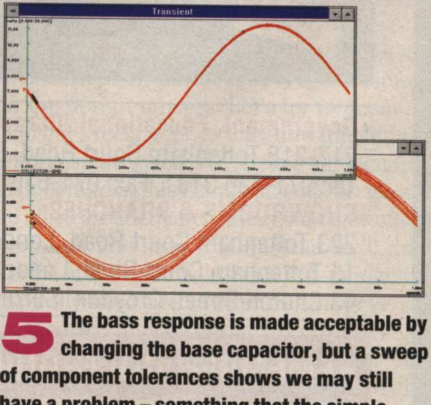
5 At long last, the circuit is working: the oscilloscope shows a pure sine wave output



3 A transient analysis shows that a 1V amplitude input signal is producing a clipped output. This will cause harmonics to be generated, as shown by the Fourier analysis



4 Changing the collector voltage cures this problem, and we now get a good clean sine wave at the output. However, the frequency response curve shows the bass response is poor



5 The bass response is made acceptable by changing the base capacitor, but a sweep of component tolerances shows we may still have a problem – something that the simple testing on the prototype didn't reveal

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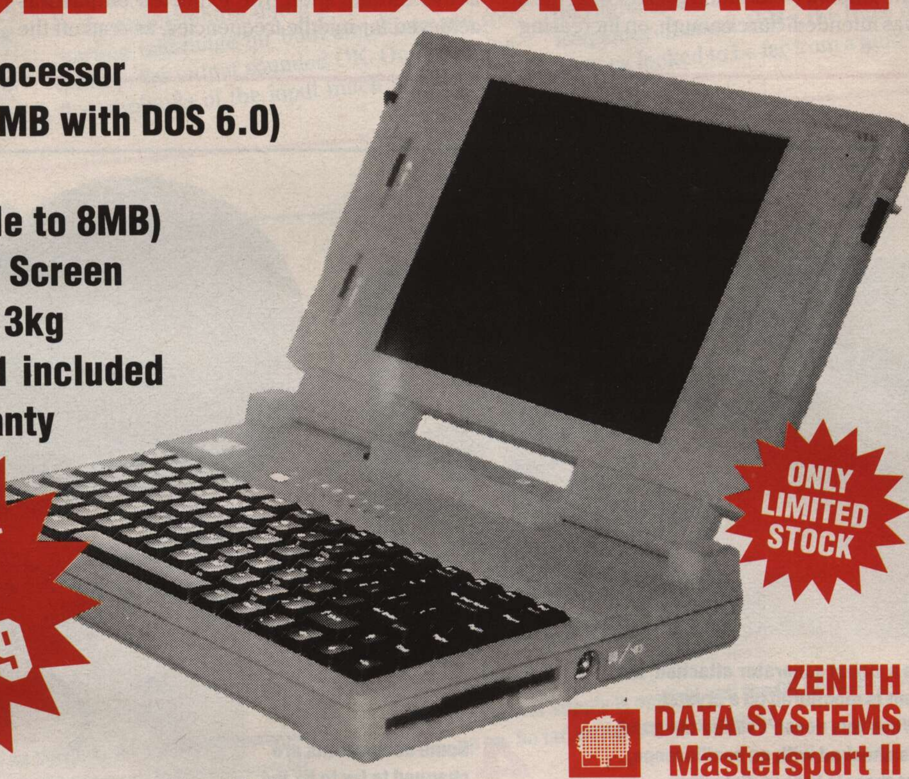

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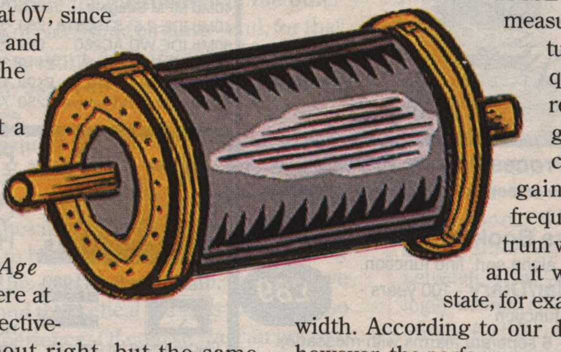
Modifying the capacitor value, on the other hand, shouldn't impact any of the other components. The 100nF capacitor was therefore changed to 1μF, and a re-testing showed that the bass response was now acceptable.

The simulation approach

THE KEY STEPS IN THE SIMULATION APPROACH are illustrated by the sequence of screendumps in Figure 3 (see panel). The first stage involved defining the circuit using the schematic capture program *GESECA* (*Graphics Entry System for Electronic Circuit Analysis*, pronounced 'Jessica'). To the user, this resembles a rather specialised drafting program – the look and feel will be reasonably familiar to anyone who's used any sort of graphics package. Essentially, components are picked out of a 'bits bucket', assigned values and tolerances, and connected up using wires. One aspect which is an obvious requirement of this type of software, but will appear somewhat different from run-of-the-mill drawing packages, is that you can move a component while leaving its connecting wires attached. The wires will 'stretch' or 'contract' as necessary, but you'll probably need to re-route them to keep the circuit diagram neat and tidy.

Unfortunately, *GESECA* isn't a *Microsoft Windows* application, although it does have its own Gui (graphical user interface), which looks remarkably similar to X-Window's *Open Look* Unix front-end. You can, of course, run it from *Windows* in the same way as any other Dos program. There's also a seamless connection to the simulation program (in our case *SPICE Age for Windows*, though other simulators are supported): the simulator program can be invoked automatically from a *GESECA* menu.

Once I'd defined the circuit in *GESECA*, I invoked *SPICE Age for Windows* to start the testing process. As with the conventional testing process, the first task was to check up on the DC operating conditions, which was done using the Analyse Quiescent DC option. Selecting this feature causes all nodes in the circuit diagram to be tabulated together with their DC voltage. Some of them are really just confirming what we already know – for example, GND is at 0V and VCC (the supply voltage) is at 12V. We can also see that the input is at 0V, since the input signal is AC and hence invisible to the quiescent analysis.



There were just a couple of nodes I was actually interested in: the transistor base and the collector. *SPICE Age* showed that these were at about 1.5 and 1.0 respectively; the base was about right, but the same couldn't be said for the collector voltage. Further investigation was called for.

Testing, testing

Clearly, with a simulator one thing we can't do is listen directly to the circuit's output as we did with the prototype board. Instead, the next step is to define the input signal and observe the output waveform. This closely parallels the phase in conventional testing where a signal generator and oscilloscope were used. In the simulation, the input signal is defined using what's effectively a 'soft' signal generator, which can produce most types of waveform for a wide range of frequencies and amplitudes. Although the circuit diagram itself defines the frequency and amplitude of the input, this can be modified using the Signal Sources Excitation Control window.

A sine wave at a frequency of 1kHz and an amplitude of 0.5V (ie 1V peak-to-peak) was picked and a good clean output waveform with a 10V swing observed using the Transient Analysis feature (which is really a simulated oscilloscope). As explained earlier, this suggested an error with the amplifier's gain, as the output should have had only a 5V swing under these conditions. On increasing the input to the maximum design amplitude of 1V, a clipped output signal was observed.

One thing I could do with *SPICE Age* that wasn't possible with the simple equipment used for the conventional testing was to carry out a Fourier analysis of the output signal. This showed the spectrum of output frequencies, and indicated that, in addition to the expected 1kHz signal, I was also getting higher harmonic frequencies. This is exactly what you would expect of a clipped signal, and explains the distortion that was clearly evident on the earpiece. The reason for the clipping, and the remedy, have already been explained. Unlike the conventional approach, which required a few minutes with a soldering iron, pliers, and solder pump, the simulated circuit was changed in just a few seconds using *GESECA* and proved to work correctly – for this mid-range frequency at least.

As with the physical prototyping and testing method, the next stage was then to repeat the above experiment at various other frequencies. With the simulator, this whole stage was greatly simplified by instructing *SPICE Age for Windows* to measure the output amplitude for a range of frequencies and plot the results as a graph of gain against frequency. The drop-off in gain towards the low-frequency end of the spectrum was blatantly obvious and it would be possible to state, for example, the 3dB bandwidth. According to our design specification, however, the performance was unacceptable, so once again a component was changed. The bandwidth graph was once again generated and so the circuit proven.

Closer inspection

This was the limit of the testing I'd done on the real board, but using *SPICE Age for Windows* other options became available. For example, the resistors and capacitors used had a tolerance of 5 percent. So, to take one instance, R2 – nominally an 18k resistor – could actually have real-world values anywhere between 17.1 and 18.9k. An important question in any design exercise is whether the circuit will still work if all the component values are on the very edge of their tolerance bands.

A 'Monte Carlo' analysis sets all the components to normally distributed random values according to their tolerances and plots the results. This gives an idea of the number of rejects if the circuit went into production. Alternatively, all the components can be set to the minimum and maximum values within the tolerance bands.

One other useful facility which could be used at this point is the subjection of the circuit to temperature extremes. Since the software's component models take account of differences due to temperature, the circuit can be tested at the limits of its intended ambient operating temperature range. Doing a scan of component tolerances through a temperature range of 0 to 30°, I generated a whole family of transient response curves. Clearly, the temperature didn't seem to be a problem, but all didn't appear to be well as regards the component tolerances.

For the purposes of this exercise I didn't investigate any further, or carry out any of the other tests which could have been performed. However, the bottom line is that although the circuit would still be some way off being passed through to production, an hour or so on the simulator (which could have been significantly reduced if it wasn't for the fact that I was simultaneously learning to use the package and generating screenshots!) had already achieved more than I'd done in double that time using conventional techniques.

The benefits

SO FAR WE'VE ONLY TALKED IN GENERAL terms about the advantages of circuit simulation to the design process. Let's try to quantify this and get a feeling for exactly how much time and effort can be saved. We'll leave our example circuit behind at this point, since it's far too simple to illustrate adequately the advantages offered in terms of time and cost. Instead we'll think in terms of the main board in a PC – a much more typically sized circuit. Even this, however, isn't a particularly difficult design exercise, being a digital circuit and having quite a number of VLSI (very large scale integration) chips. With analogue projects, and particularly those using discrete components, the saving could be much greater.

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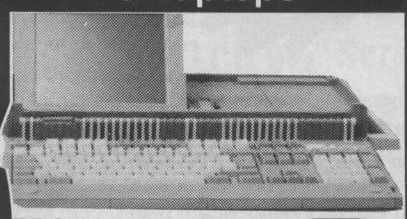

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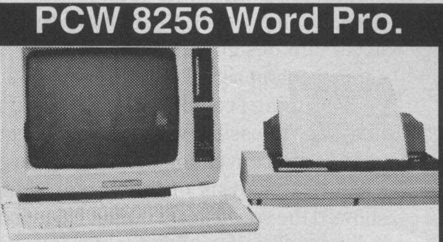

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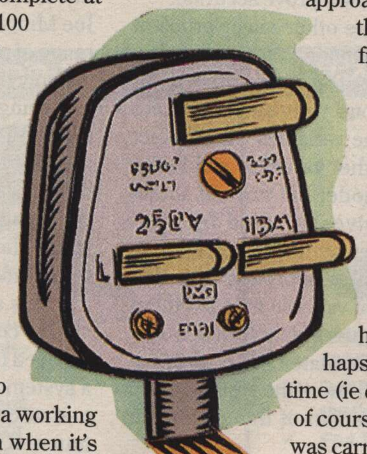
physical laying-out of the board, that is; we're assuming the theoretical design is complete at this stage). Prior to manufacture, £100 worth of photography and £100 spent on tooling is required. The boards themselves will then cost in the region of £200 each for a batch of half-a-dozen boards – the sort of volume normally used for prototyping.

Why are we are assuming six boards will be prototyped? Working with more than one board speeds up the process by allowing different engineers to work on different aspects of the testing, and also gives some degree of confidence that a working prototype will still work in production when it's subjected to the slight differences which occur between two supposedly identical components.

Finally building up the boards would cost about £150 each, excluding the component cost – let's say a further £50 each. How much time will it then take to test the prototype and get it working? Well, that's like asking how long is a piece of string. We could easily be talking a couple of weeks or so of a design engineer's time; a conservative estimate of the cost of this would be £2,000. This brings us to a grand total of £5,200.



A slight saving with the conventional approach is made possible by the fact that, unless the first prototype is totally wrong, the final PCB design can use the prototype design as a starting point, so this task will be less expensive than it would be following simulation.

The simulation approach, on the other hand, would cost perhaps a week of the engineer's time (ie circa £1,000), assuming, of course, that the initial design was carried out on a Cad system so that the engineer didn't have to key all the connectivity information into the simulation package.

The reasoning

ON THE FACE OF IT, THEN, ELECTRONIC CIRcuits would appear to be an ideal candidate for computer simulation – in marked contrast to the economy, the modelling of which we investigated last month. The modelling process doesn't seem too arduous, and the results appear to be both accurate and reliable as a design tool. So why is this? What's the big difference?

The simple answer is to say that (in nearly all cases) electronic circuits don't exhibit the properties we identified last month as the ones that make economic modelling so problematic. To be a little more precise, let's briefly summarise these points and thus outline those aspects which make a system suitable for simulation.

Before starting, I should point out that in taking economics and electronics as our first two illustrations of computer modelling, we've picked what must surely be considered about the worst and best possible scenarios. Most simulation exercises will come somewhere between these two extremes, exhibiting some of the difficulties associated with modelling the economy and some of the accuracy of modelling circuit design.

Electronics is a physical science: that is, it's concerned with the properties and behaviour of things. Economics, on the other hand, is a social science: it's concerned with people, what makes them tick, how they think and how they behave. The difficulty of dealing with human factors is a point we kept coming back to in our treatment of economic modelling. In particular, we discussed

Big is, er, expensive

VLSI stands for 'very large scale integration', and is one of the four somewhat arbitrary classifications of chips or integrated circuits (ICs). The other three of these highly technical terms are SSI (small scale integration), MSI (medium scale integration), and LSI (large scale integration), and the differentiation is made, as you might well have guessed, on the basis of size – that is, the number of transistors. What I'm going to say here about VLSI also applies to the other categories of IC, but – for obvious reasons – is more pronounced at the top end of this continuum.

We've already discussed how a conventional circuit is manufactured by soldering individual components onto a printed circuit board. A VLSI chip, by contrast, is a sub-circuit which is fabricated by microscopically etching each component and the interconnecting tracks onto a single 'chip' of silicon. VLSI design has traditionally been the domain of specialist semiconductor manufacturers – Intel, AMD et al – but advances in Asic (application-specific integrated circuit) technology have meant that it's now undertaken by 'ordinary' electronics companies as an alternative to the use of discrete components. Compared to conventional techniques, the use of VLSI technology gives savings in size and weight, and – as long as the ICs are manufactured in sufficient quantity – a major cost saving too.

In practice, we can't draw a neat dividing line between the 'conventional' and the 'integrated' approach, because an integrated circuit is never used by itself. It always acts as a component part of a more complex circuit which is, of course, built up on a printed circuit board. A look at the main board in your PC will verify this. Most of the components will be ICs; discrete components are comparatively rare on this sort of circuitry.

Alpha better

A microprocessor is a classic case of a VLSI device. As an example of what's involved in developing a microprocessor, we'll look at some facts and figures regarding Digital's new Alpha processor, which looks set to compete with Intel's Pentium in top-of-the-range PCs. The 21064 chip (Alpha is the name of the architecture, not of individual microprocessors within the family) has the equivalent of 1.68 million transistors on a die measuring 14x17mm. An obvious question is how on earth a design engineer goes about prototyping and testing a circuit of such mind-blowing proportions.

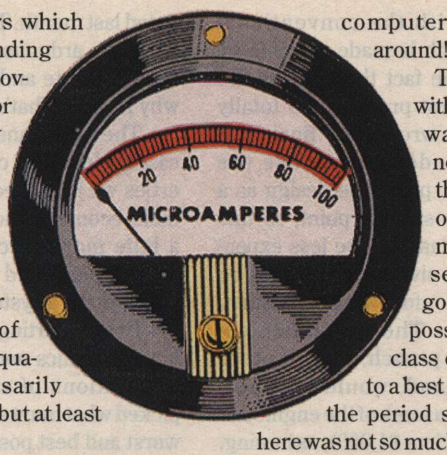
If the advantages offered by circuit simulation are significant for electronic design at the circuit board level, VLSI design must offer the ultimate opportunity for simulation. What we're talking about here isn't just an easing of the design process by computer technology, but an enabling of something which otherwise just wouldn't be possible. Processor design has now got to the stage where a new processor couldn't be developed without a bit of assistance from the previous generation. A major part of this enabling concerns Cad – computer assistance in the actual design and layout of the chip – but simulation is also a key technique.

Elsewhere we've compared the physical prototyping and testing of a PC's main board with computer simulation. Let's consider the Herculean task of prototyping something the size of an Alpha processor. A rough estimate of the size of a mock-up of such a chip, using SSI devices (based on the assumptions that an average TTL chip contains the equivalent of 100 transistors and that around 80 of these can be crammed onto one PCB), comes out at around 200 PCBs, each about the size of the main board in a PC. From the figures given earlier, this would suggest a prototyping cost in the region of half a million pounds.

If this is something of an eye-opener, what about the testing cost? This wouldn't just be a factor of 200 greater than the previous quoted figure – you have to take into account the testing of the myriad interconnections between the 200-odd boards. Quite clearly, what we've proposed just isn't a viable proposition.

So let's try an alternative scenario: prototyping the circuit as a chip, not a mock-up using discrete components. After all, we've said ICs are much cheaper than the same circuitry implemented conventionally. You'll remember, however, that this statement was conditional on sufficient volumes being manufactured. The reason for this is that there's a phenomenal up-front cost to IC semiconductor manufacture, which is normally shared out between hundreds of thousands of units produced. For prototyping, this initial cost – which would remain exactly the same – would be spread over tiny volumes, so the cost per unit would go through the roof. Even that isn't the limit of the difficulties faced with this approach. Testing something 14x17mm with the equivalent of 1,680,000 transistors isn't exactly a run-of-the mill task.

In short, we're up another blind alley. The only answer is to carry out the prototyping without building and testing actual ICs – in other words, by simulation.



how so many of the factors which affect the economy – spending habits, voting patterns and government policy decisions, for example – were virtually impossible to predict. Not only that, but publishing the results of an economic forecast can influence the very things that were predicted. In contrast to the behaviour of people, the behaviour of things is defined by exact equations. This doesn't necessarily mean it's totally predictable, but at least it's a start.

The point at which objects cease to behave predictably is where we get into the realm of chaos. We described the economy, at least in part, as a chaotic system. Other than saying that this meant the system had extreme sensitivity to the initial conditions, we didn't elaborate on the point. Well, you're still going to have to wait for an in-depth treatment; since chaos theory is a major aspect of simulation, we're going to dedicate a whole article in this series to the topic later on. For now, let's just say that one thing which makes electronic circuits such a joy to simulate is that they're not normally chaotic.

I have to add the rider 'normally' because fractals and chaos are currently the flavour of the month (of the last 25 years, to be more precise) and there are now very few disciplines in which chaos theory has not reared its head. Electronics is no exception, and circuits have indeed been designed to exhibit chaotic properties. If you're particularly interested in this, I suggest you take a look at the article 'Chaos on the Circuit Board' by Jim Lesurf, *New Scientist*, June 30th 1990, pp63-66.

You never can tell

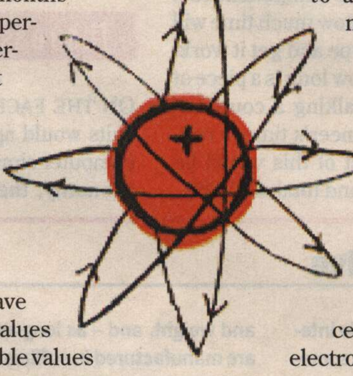
Even if a system behaves in a predictable manner, that doesn't necessarily mean we can accurately define its behaviour in terms of equations. You'll recall that a major difficulty with economic modelling was the derivation of the equations. Typically, economic relationships have to be determined empirically – that is, by observing historical trends and assuming that the same patterns will hold true for the future. On the other hand, models of electronic circuits – and, for that matter, many systems described by the physical sciences – are based on equations derived from first principles.

When we quote the equation associated with Ohm's Law, V=IR, we aren't just saying that the volt drop across a resistor is *approximately* proportional to the current flowing through it, or that this *appears* to be the relationship. We're saying that this is the exact relationship, and that we have very good theoretical reasons for saying so – not just experience. Of course, we can get into philosophical arguments – 'When is a first principle really a first principle?' and 'Don't all these laws really come down to observation in the final analysis?' are awkward questions that spring to mind – but in practice, we can assume that simulations based on the generally accepted laws of the physical sciences (laws which, in many cases, have been known for much longer than computer simulation has been around!) will prove accurate.

The other major problem with modelling the economy was the issue of 'exogenous' variables. These are the variables which affect other variables within the model but are not themselves affected by what goes on within it. The only possible approach with this class of variable is to set them to a best guess of their values over the period simulated. The problem here was not so much one of the system under investigation, but of the aim of the simulation exercise.

Straight answers

In modelling the economy, the intention is to make some statement like 'In six months' time, the inflation rate will be 2 percent, there will have been 0.5 percent growth in GDP over the last quarter, and unemployment will stand at 3,000,000'. Really, a rather more honest answer would be to give a whole range of predictions based on all the possible values for the exogenous variables.



So, for example, we would have to give forecasts for all possible values of German interest rates, all possible values for the volume of world trade, and so on. Clearly, this isn't an acceptable approach – Joe Public (or Joe Minister) wants a single answer, not a whole range of possible outcomes to which he then has to apply his own judgement.

Things are quite different with electronic circuits. All the variables that are external to the model are either under the direct control of the designer (eg the supply voltage) or within a specified range (as in the case of temperature) over which the designer is responsible for ensuring the circuit will function correctly.

This stresses the fact that simulation is not always concerned with prediction. In this case we need to be able to state what would happen to a system under given sets of conditions, but not to state categorically how a unit will behave in the future. If we were concerned with prediction, circuit simulation would, for example, be required to prophesy that a particular laptop computer, once manufactured, would be exposed to a light shower after three months, subsequently operated while upside-down, and six weeks later flattened by a 14-ton weight.

When you look at it this way, economic modelling begins to seem even sillier than it did before, and it's clear that we shouldn't be surprised to achieve so much greater success in the more exact science of electronics. ■

Contacts

GESECA and *SPICE Age for Windows* are the products used here to illustrate circuit simulation. Both are available from **Those Engineers Ltd** on (081) 906 0155. *SPICE Age* is available at several levels, the differences lying in the facilities offered and the size of the component libraries. *SPICE Age*'s forté is analogue simulation, although simple logic gates are provided as part of the library.

Those Engineers also provide a range of other software tools for the electronic design engineer, including solutions for digital circuit simulation. *GESECA* costs £195, *SPICE Age for Windows* between £395 and £545. The logic design simulator, *LCA-1*, costs £450. All prices are exclusive of Vat and carriage. Multi-user education licences are available at discount.

Another British company which is well established in this field is **ARS Microsystems Ltd** on (0256) 381400. The *PSpice Design Centre* range is an integrated suite of programs for schematic capture and circuit simulation, both analogue and digital. Platforms supported include PC (Dos or *Windows*), Macintosh and Sun SPARCstation. Prices for the PC vary from £95 (for an evaluation version which doesn't include the schematic capture and is limited in the size of circuit supported) to £7,500 for the top-of-the-range version.

SPICE, in case you're wondering, is the name of a program which originated at the University of California at Berkeley and has become adopted as the de facto standard for analogue circuit simulation. It has since has spawned many commercial derivatives for many platforms, of which *PSpice* is one. Despite its name, *SPICE Age* is not fully *SPICE*-compliant (which is only a disadvantage if you're already conversant with *SPICE*), although at level 7 you do get the ability to import *SPICE* component models.

A good guide to circuit simulation in general, and *SPICE* in particular, is Paul W Tuinenga's *A Guide to Circuit Simulation & Analysis Using PSpice*, 2nd Edition, (ISBN 13 747270 6). It's published by **Prentice Hall** and costs £21.50. Although the author of this book certainly expects his readers to have some knowledge of electronics, it really isn't too heavy going, taking a tutorial approach and working through lots of examples.

Editions of the book packaged with the Student Version of *PSpice* (as opposed to the commercial version which ARS distributes) are also available for the PC. The title code numbers are #73500-1 and #73501-9 for 3.5" and 5.25" disks respectively.

The Student Versions of *PSpice* are also available separately in the formats mentioned above (codes #73475-6 and #73476-4 respectively) and also for the Apple Macintosh (#73474-9). Prentice Hall is on (0442) 881900.